Aerothermodynamics of a Simple Resonance Tube

C. E. G. Przirembel*
Rutgers University, New Brunswick, N. J.
and
L. S. Fletcher†
University of Virginia, Charlottesville, Va.

An experimental investigation of a simple resonance ignition tube has been conducted. The leading edge of the resonance tube was blunt in order to simulate the geometry of proposed rocket ignition systems. The jet-stagnation pressure, the nozzle/resonance-tube separation distance, and the resonance-tube length were varied systematically. Strong resonance was found to occur when the leading edge of the resonance tube was located within the third compression cell of the underexpanded jet. High-speed motion pictures showed a significant upstream propagation of disturbances from the resonance tube to the nozzle. These results will be useful in determining the feasibility of using resonance-tube ignition systems for both liquid- and solid-propellant rocket engines.

Nomenclature

D = jet-exit height
L = length of resonance tube
P_a = atmospheric pressure
P_0 = jet-stagnation pressure
S = distance between nozzle exit and resonance-tube inlet
T_0 = jet-stagnation temperature
T_w = resonance-tube endwall temperature

Introduction

ONE of the problems associated with the use of oxygen/hydrogen bipropellant rocket engines, such as proposed for the space-shuttle main engine and the space-shuttle auxiliary propulsion engines, is that of designing a simple, highly reliable method for multiple ignitions. Currently, one of the most common ignition systems utilizes high-energy spark igniters.[1,2] Major problems associated with this system are electrical complexity, power consumption, and weight. An alternate ignition technique, which avoids these problems, is based on the thermophysics phenomena of the resonance tube.

A simple resonance tube consists of a cavity having the open end axially aligned with a suitable high-velocity flowfield. Resonance, which is characterized by high-frequency oscillations in the cavity, is initiated when instabilities in the impinging flowfield are in synchronization with the natural frequency of the gas in the tube. This phenomenon has been observed for various cavity and flowfield combinations. For example, resonance can occur for either two-dimensional or axisymmetric cavities, when placed in flowfields associated with supersonic wind tunnels, choked nozzle jets, or supersonic free jets generated from a correctly expanded nozzle.

The internal cavity flow is characterized by periodic traveling shock and expansion waves. The periodic compression and expansion of the portion of the gas retained in the cavity results in irreversible increases of temperatures, which are significantly higher than the jet adiabatic stagnation temperature. Endwall temperatures on the order of 752°F (400°C) have been measured with nitrogen and 2192°F (1200°C) with helium.[3] Hence, by a thermophysics phenomenon, this device converts flow energy to thermal energy, as well as acoustic energy.

The resonance-tube phenomenon was described first by Hartmann.[4] During an investigation of the axial stagnation pressure distribution of an underexpanded sonic jet, high-amplitude pressure oscillations occured when the pitot tube was located in certain portions of the jet flowfield. Hartmann and his co-workers[5-10] became interested in this phenomenon primarily as a means of generating acoustical signals. Other investigators have followed this research direction and have studied and developed various devices as acoustic generators.[11-14]

Sprenger[15] was the first investigator to report the thermal aspects of the resonance tube. This experimental study was directed toward the measurement of average wall pressure, average wall temperature, and sound intensities as a function of tube geometry and stagnation pressure. Temperatures as high as 797°F (425°C) were measured. Because of the obvious practical applications of this thermal phenomenon, there has been considerable experimental effort to establish the dependence of the heating effect upon the fluid flow operating parameters and various geometric configurations of the resonance tube. Cassidy et al.[16] verified the dependence of maximum temperature rise on the jet stagnation pressure and geometry. The existence of shock waves within the resonance tube was observed optically by Vrebalovich,[17] Lloyd,[18] and Hall and Berry.[19] Recently, endwall temperature-time histories for various geometries and operating conditions have been reported by Gehman and Campagnuolo[20] and by Rakowsky et al.[21]

Because of the highly complex flow interactions, only some limited theoretical analysis has been published to date. Thompson[22,23] constructed wave diagrams for the resonance tube flow and estimated heating effects by computing entropy production. Kang[24] analyzed the stagnation stability of a resonance tube excited by a correctly expanded, supersonic nozzle. Also, it was shown that, for an ideal, inviscid gas, the maximum endwall temperature was of the order of 10 times the jet adiabatic stagnation temperature.

Application of this gasdynamic resonance phenomenon to the rocket-ignition problem was proposed first by Phillips et al.,[25] and the reported results demonstrated the feasibility of utilizing the resonance effect to ignite stoichiometric mixtures of gaseous hydrogen and oxygen. Marchese et al.[26] developed

Presented as Paper 75-687 at the AIAA 10th Thermophysics Conference, Denver, Col., May 27–29, 1975; submitted June 24, 1976; revision received Sept. 20, 1976.

Index category: Nonsteady Aerodynamics.

*Associate Professor, Dept. of Mechanical, Industrial, and Aerospace Engineering. Associate Fellow AIAA.

†Professor and Chairman, Dept. of Mechanical Engineering. Associate Fellow AIAA.

and demonstrated a fluidic-ignition system for solid-propellant rocket engines. More recently, Stabinsky[27] reported the results of an analytic study delineating potential uses of resonance ignition in oxygen/hydrogen bipropellant and hydrazine monopropellant rocket engines.

There are a number of methods for utilizing the resonance phenomenon for ignition purposes.[27] The principal difference between this type of resonance tube and most of the geometries previously investigated is that the resonance tube leading edge of the ignition system is blunt, whereas the other resonance tubes either were thin-walled or had a sharp leading edge. Only very recently has it been recognized that this geometric difference significantly changes the flowfield[28,29] and, therefore, must be taken into account in the design of ignition systems.

This paper presents the results of an experimental investigation of the flowfield associated with an underexpanded, two-dimensional choked nozzle and a two-dimensional resonance tube with a blunt leading edge. Resonance-tube endwall temperatures and pressures were measured for various resonance-tube lengths and nozzle-exit-to-resonance-tube inlet separation distances. The jet-stagnation pressure also was varied. Both still photographs and high-speed motion pictures were obtained of the flowfield utilizing color schlieren, conventional schlieren, and shadowgraph techniques. The results provide significant new physical insight into the complex thermophysics processes governing the resonance phenomenon.

Experimental Program

A two-dimensional nozzle/resonance-tube combination was chosen in order to provide a simple geometry for optical studies of the flowfield. A schematic of the model, indicating appropriate geometrical parameters, is shown in Fig. 1.

The jet was generated by an underexpanded choked nozzle. The contraction ratio was 5:1, and the rectangular exit was 0.5 (1.27)×0.5 in. (1.27 cm). The actual nozzle contour in the flow direction was elliptical. The resonance tube was also rectangular in cross section, with an entrance height d of 0.63 (1.60) and 0.5 in. (1.27 cm) (along the optical path). The larger resonance-tube area was deemed necessary to compensate for the jet spreading associated with the primary jet flow. The endwall was designed to accommodate thermocouples for temperature measurements and a pressure orifice for time-averaged pressures. The length-to-height ratio (L/D) was adjustable in discrete steps by moving the endwall. For the optical studies, preliminary temperature measurements, and pressure measurements, the resonance tube was constructed from cold-rolled steel or aluminum. Hence, the associated heat conduction insured that the endwall temperatures were maintained at levels slightly above ambient conditions, and damage to the optical windows by thermal shock was alleviated. For the final endwall temperature measurements, the resonance tube and sidewalls were constructed from bakelite.

Results and Discussion

The variable test parameters were the ratio of resonance-tube length to nozzle-exit height (L/D), the ratio of the separation distance between nozzle exit and resonance-tube inlet to nozzle-exit height (S/D), and the nozzle-flow stagnation pressure (P_0). Table 1 lists the range of these test variables. The range of these variables was chosen on the basis of previously published results of the occurrence of strongest resonant conditions and practical size limitations for resonance-tube ignition systems. The nozzle-flow stagnation temperature was the atmospheric temperature. For the optical studies in which the entire flowfield of the jet and resonance tube was recorded simultaneously, the sum of the former two geometric parameters (L/D, S/D) did not exceed the characteristic dimension of the existing optical field.

Some typical results for $L/D=4.0$ are presented in Figs. 2 and 3. Figure 2 illustrates the variation of the time-averaged resonance-tube endwall pressure with nozzle/resonance-tube separation distance as the jet-stagnation pressure is increased. Without the existence of gasdynamic resonance phenomenon, these curves would be representative of the jet centerline pitot pressure. In fact, for the lowest jet stagnation pressure, the data show quite clearly the pressure variation expected for a subsonic jet. As the jet stagnation pressure increases, the nozzle is choked and then becomes more and more underexpanded. An effective indicator of the extent of underexpansion is obtained by nondimensionalizing the jet

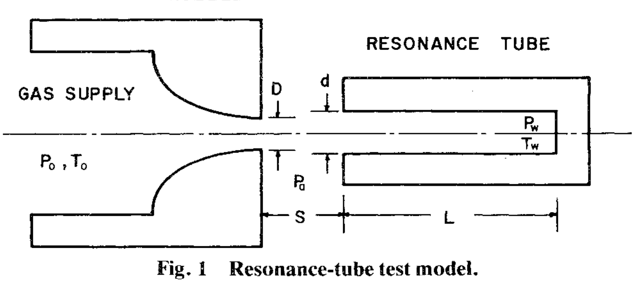

Fig. 1 Resonance-tube test model.

Table 1 Range of test parameters

Parameter	Range
L/D	1.0– 10.0
S/D	1.0– 6.0
P_0, psig	10.0–100.0
(N/m^2)	(6.9×10^4–6.9×10^5)

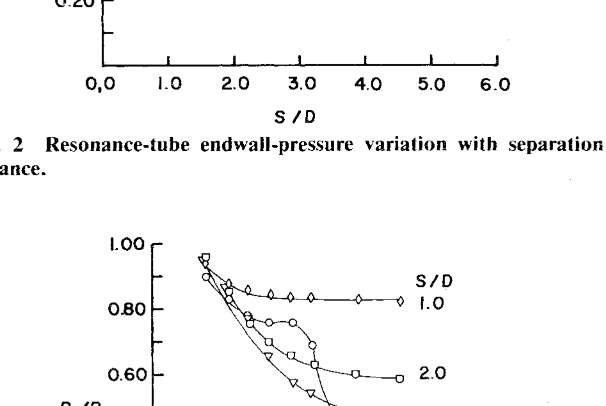

Fig. 2 Resonance-tube endwall-pressure variation with separation distance.

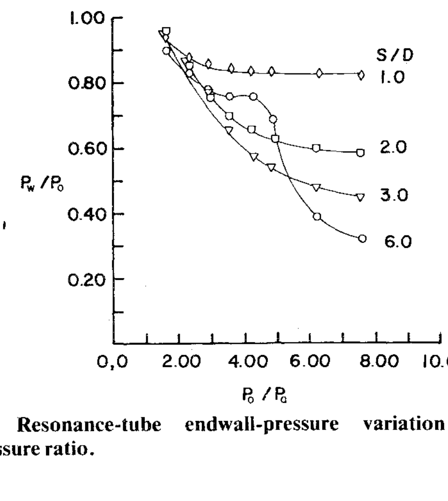

Fig. 3 Resonance-tube endwall-pressure variation with jet-overpressure ratio.

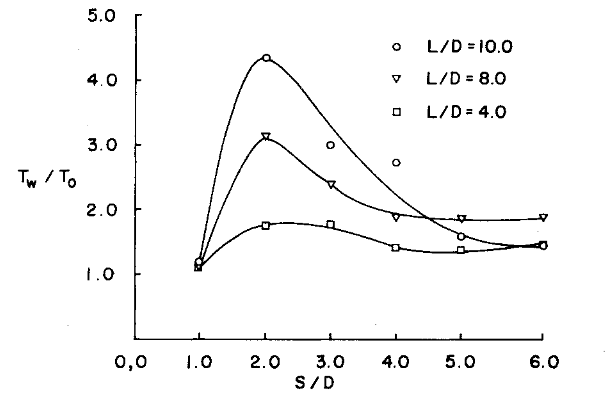

Fig. 4 Maximum resonance-tube endwall-temperature variation with separation distance.

stagnation pressure with the ambient pressure (P_0/P_a). From one-dimensional gasdynamics, choked flow occurs for $P_0/P_a = 1.89$. For values of P_0/P_a equal to *1.68, 2.28, 6.21,* and *7.57*, the measured pressures decrease monotonically in the downstream direction, as expected. However, for $P_0/P_a = 3.57$ and *4.85*, the endwall pressure increases for S/D greater than *3.0*. This phenomenon is illustrated in Fig. 3.

For several combinations of S/D and L/D there was a range of values of P_0/P_a for which P_w/P_0 remained essentially constant. This can be seen in Fig. 3 for $S/D = 6.0$. Phillips and Pavli[30] observed that the measured resonance-tube endwall pressure-wave amplitude reached a plateau for values of L/D greater than seven. For the data presented in Ref. 30, P_0, P_0/P_a, and S/D were fixed. Without a knowledge of the detailed pressure distribution in the actual jet or schlieren photgraphs, it is not possible to provide an adequate explanation of this phenomenon. Figure 4 provides clear evidence of the existence of the resonance-tube phenomenon for all test conditions except $S/D = 1.0$. This figure presents the maximum value of the resonance-tube-endwall-temperature/jet-stagnation-temperature ratio for some typical values of L/D over the present range of stagnation pressure. For a given L/D , both S/D and P_0/P_a values were varied systematically during the experimental program. For each combination of test variables, the resonance-tube endwall temperature and the jet-stagnation temperature were measured. For a given L/D and S/D, a maximum of T_w/T_0 was obtained at some value of P_0/P_a. Of particular interest was the fact that, in some cases (for instance, $S/D = 2.0$, $L/D = 10$), the maximum temperature ratio was obtained at very low jet-stagnation pressure. From Fig. 4, it also can be observed that the strongest resonance condition occurs at lower values of S/D as the relative length of the resonance tube is increased. Phillips et al.,[25] working with a stoichiometric mixture of hydrogen and oxygen gases in an axisymmetric resonance tube, observed exactly the opposite trend. Their results were restricted to a single value of P_0/P_a, and a relatively small range of S/D values. The region between $S/D = 1.0$ and $S/D = 3.0$ is obviously of primary importance for rocket-ignition systems and needs to be explored in more detail. Furthermore, it is clear that the maximum attainable temperature is a strong function of the resonance-tube length, and additional data are required to determine the existence of an upper limit of L/D for which the endwall temperature reaches its ultimate maximum.

Comparing the color schlieren photographs with the S/D values for strong resonant conditions, it was observed that the resonance-tube inlet was located in the third compression cell of the underexpanded jet. This is in contrast with the results reported by other investigators,[15,31] who recommended placing the resonance-tube inlet in the first or second compression cell. This difference may very well be due to the large, blunt leading edge of the current model and the relatively short tube length.

All of the high-speed motion-picture flow-visualization techniques indicated density variations in the resonance tube. However, there was no clear evidence of a normal shock moving back and forth as observed by previous investigators This phenomenon can be attributed to the particular geometric configuration of the current resonance tube, i.e., a blunt leading edge. A careful review of the water table study by Skok and Page[29] has shown that a normal shock (hydraulic jump) existed for a resonance tube with a sharp leading edge but did not develop for the blunt leading edge. It should be noted that all of the previously published flow visualization studies utilized sharp-edged or thin-walled resonance tubes and large values of L/D. Hence, strong normal shocks were observed by the use of the shadowgraph technique.

The shadowgraph film, as well as the other two techniques, showed that, during the collision of the outflow from the resonance tube and the nozzle jet, pressure disturbances propagated to the nozzle-exit plane. The associated pressure changes resulted in variations of the initial nozzle expansion-wave angles. This observation seems to strengthen the arguments used by Kang[24] in analyzing the stability of resonance flow. The same phenomenon was observed also on the water table by Skok and Page.[29]

Conclusions

This paper reports the results of an experimental investigation of a simple resonance ignition tube. The major difference between the model and previously investigated resonance tubes is that the leading edge of the tube was blunt rather than sharp. The jet-stagnation pressure and the two major geometric parameters were varied. The results indicate that strong resonant conditions are dependent on the jet-stagnation pressure and the separation distance between the nozzle and the tube. For the blunt leading edge and low values of L/D, the third compression cell of the underexpanded jet seems to be most conducive to strong resonance. High-speed motion pictures indicated a significant upstream propagation of disturbances from the resonance tube to the nozzle. Furthermore, no strong normal shock was observed in the resonance tube. These results will be useful to design engineers in determining the feasibility of replacing current high-energy spark-ignition systems for both liquid- and solid-propellent rocket engines with resonance ignition systems.

Acknowledgment

The authors would like to thank David E. Wolf for assisting in the experimental portion of this work. The Rutgers Research Council provided partial financial support for his research.

References

1 "Engine Design Definition Report, Combustion Devices," Rept. RSS-8504-3, April 1971, Rocketdyne.

2 Lauffer, J. F., "Space Shuttle Auxiliary Propulsion (APS) Ignition System," NASA CR-72972, May 1971.

3 Wu, J. H. T., Ostrowski, P. P., Neemeh, R. A. and Lee, P. H. W., "Experimental Investigation of a Cylindrical Resonator," *AIAA Journal,* Vol. 12, Aug. 1974, pp. 1076–1078.

4 Hartmann, J. and Troll, B., "On a New Method for the Generation of Sound Waves," *Physical Review,* Vol. 20, Dec. 1922, p. 719.

5 Hartmann, J., "On the Production of Acoustic Waves by Means of An Air-Jet of a Velocity Exceeding that of Sound," *Philosophical Magazine,* Vol. 11, April 1931, p. 926.

6 Hartmann, J. and Mathes, E. V., "Die Experimentelle Grundlage Zum Entwurf des Akustichen Luftstrahlgenerators," *Akustiche Zeitschrift,* Vol. 4, 1939, p. 126.

7 Hartmann, J., "The Hartmann Acoustic Generators," *Engineering,* Vol. 142, Nov. 1936, p. 491.

8 Hartmann, J., "Construction, Performance, and Design of an Acoustic Air-Jet Generator," *Journal of Scientific Instruments,* Vol. 16, April 1939, p. 140.

[9]Hartmann, J. and Lazarus, F., "The Radiation of the Acoustic Air-Jet Generator Derived from Direct Observations of the Amplitude of the Aerial Vibrations of the Oscillator," *Philosophical Magazine,* Vol. 29, Feb. 1940, p. 140.

[10]Hartmann, J. and Larris, F., "The Air-Jet Generator as a Means of Setting Up Waves in a Liquid Medium," *Klg. Danske Widensk. Selsk. Math.-Fys. Medd.,* Vol. 26, 1951, p. 11.

[11]Boucher, R. M. G. and Brun, E., "Research on the 'Multiwhistle' Acoustic Air-Jet Generator," *Engineering Digest,* Vol. 17, 1956, p. 511.

[12]Brun, E. and Boucher, R. M. G., "Research on the Acoustic Generator: A New Development," *Journal of the Acoustic Society of America,* Vol. 29, May 1957, p. 573.

[13]Morson, A. O. and Binder, R. C., "Intensities Produced by Jet-Type Ultrasonic Vibrators," *Journal of the Acoustic Society of America,* Vol. 25, Sept. 1953, p. 1007.

[14]Savory, L. E., "Experiments with the Hartmann Acoustic Generator," *Engineering,* Vol. 170, Aug. 1950, pp. 99, 137.

[15]Sprenger, H. S., "Uber Thermische Effekte Bei Rezonanzrohren," *Mitteilungen Aus Dem Institut Fur Aerodynamik An Der E. T. H.,* Zurich, No. 21, 1954, p. 18.

[16]Cassidy, E. C., Thompson, R. C., and Slawsky, M. M., "Investigation of Resonance Tube Heating," Rept. 4301, 1957, National Bureau of Standards, Washington, D. C.

[17]Vrebalovich, T., "Resonance Tubes in a Supersonic Flow Field," Rept. 32-378, 1972, Jet Propulsion Lab., California Institute of Technology, Pasadena, Calif.

[18]Lloyd, E. C., "Pressure Wave Propagation in a Resonance Tube," Rept. 6443, 1958, National Bureau of Standards, Washington, D. C.

[19]Hall, I. M. and Berry, C. J., "On the Heating Effect in a Resonance Tube," *Journal of the Aerospace Sciences,* Vol. 26, April 1959, pp. 253-254.

[20]Gehman, S. E. and Campagnuolo, C. J., "Heat Generation in Small Resonance Tubes," Rept. AD863557, 1969, Harry Diamond Laboratories.

[21]Rakowsky, E. L., Corrado, A. P., and Marchese, V. P., "Fluidic Explosive Initiator," *Proceedings of the Sixth Cranfield Fluidics Conference,* Cambridge, England, Paper H4, 1974, p. 29.

[22]Thompson, P. A., "Resonance Tubes," ScD. Thesis, 1961, Massachusetts Institute of Technology, Cambridge, Mass.

[23]Thompson, P. A., "Jet-Driven Resonance Tube," *AIAA Journal,* Vol. 2, July 1964, pp. 1230-1233.

[24]Kang, S. W., "Resonance Tubes," Ph.D. Thesis, 1964, Rensselaer Polytechnic Institute, Rensselaer, N. Y.

[25]Phillips, B., Pavli, A. J., and Conrad, E. W., "A Resonance Igniter for Hydrogen-Oxygen Combustors," *Journal of Spacecraft and Rockets,* Vol. 7, May 1970, pp. 620-622.

[26]Marchese, V. P., Rakowsky, E. L., and Bement, L. J., "A Fluidic Sounding Rocket Motor Ignition System," *Journal of Spacecraft and Rockets,* Vol. 10, Nov. 1973, pp. 731-734.

[27]Stabinsky, L., "Analytical and Experimental Study of Resonance Ignition Tubes," Final Rept. R-9403, 1973, Rocketdyne.

[28]Skok, M. W. and Page, R. H., "An Analog Investigation of the Gas Jet Resonance Tube," *Proceedings of the Fifth Cranfield Fluidics Conference,* Paper D3-37, 1972.

[29]Skok, M. W. and Page, R. H., "An Analog Investigation of the Gas Jet Resonance Tube," 16-mm silent color motion picture, 1972, Dept. of Mechanical, Industrial and Aerospace Engineering, Rutgers Univ., Rutgers, N. J.

[30]Phillips, B. R. and Pavli, A. J., "Resonance Tube Ignition of Hydrogen-Oxygen Mixtures," Nasa TN D-6354, May 1971.

[31]Pavlak, A., "Tapered Resonance Tubes," M.S. Thesis, 1968, Mechanical Engineering Dept., Stevens Institute of Technology, Hoboken, N. J.